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The Parallel Operation
Of Distant Alternators

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THE PARALLEL OPERATION
OF
DISTANT ALTERNATORS

BY

DANIEL CLEVELAND FABER
HERBERT EDWARD KAHLERT

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FOR THE
DEGREE OF BACHELOR OF SCIENCE
IN
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DANIEL CLEVELAND FABER and HERBERT EDWARD KAHLERT

ENTITLED PARALLEL OPERATION OF DISTANT ALTERNATORS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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THE PARALLEL OPERATION OF DISTANT ALTERNATORS.

In the investigation of "The Parallel Operation of Distant Alternators", it has been the aim of the authors of this thesis to study the subject not only by experiment, but also by the observation of actual working conditions in several plants having alternators working in synchronism with others at a distance. The results of the latter investigations, while not numerical, form a very valuable portion of the data collected, and represent conditions which may be encountered in commercial plants attempting to operate machines in parallel with others at a considerable distance. Information so obtained was used as a foundation upon which to base experimental work, in an effort to obtain numerical data which would show the approximate relation between the various factors which determine the limits of satisfactory operation under the conditions above named. These experiments, of course, could not cover as wide a range of operation as occurs in commercial practise, for several reasons, chief of which was the lack of transmission equipment such as is actually used.

In order to limit the scope of the subject, the operation of the machines after synchronizing was investigated, and not the method of bringing them into a state of synchronism; it being assumed that for all cases the machines can be brought, at least for no-load conditions, into a proper parallel running relation.

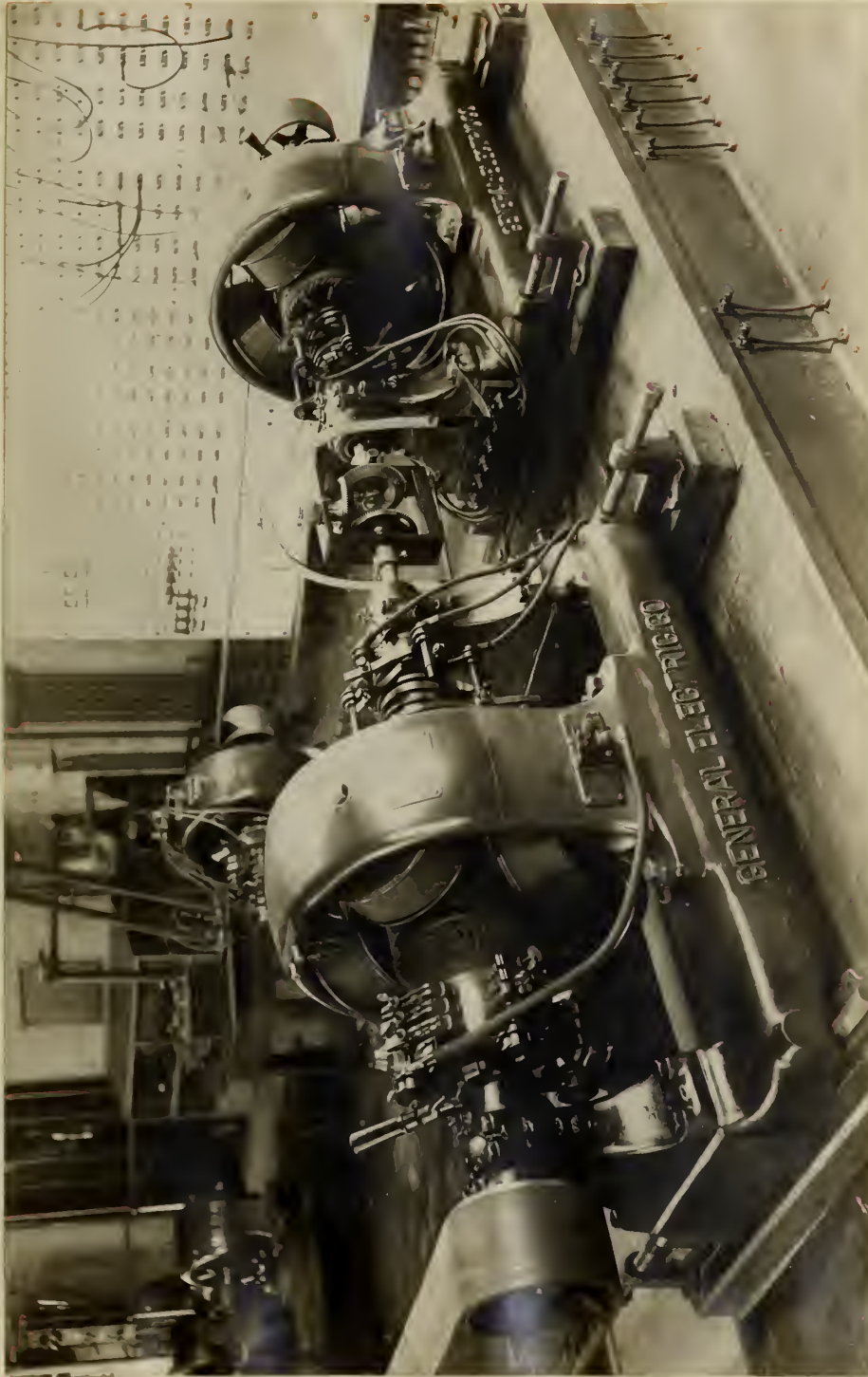


Figure 1, General View of Machines.

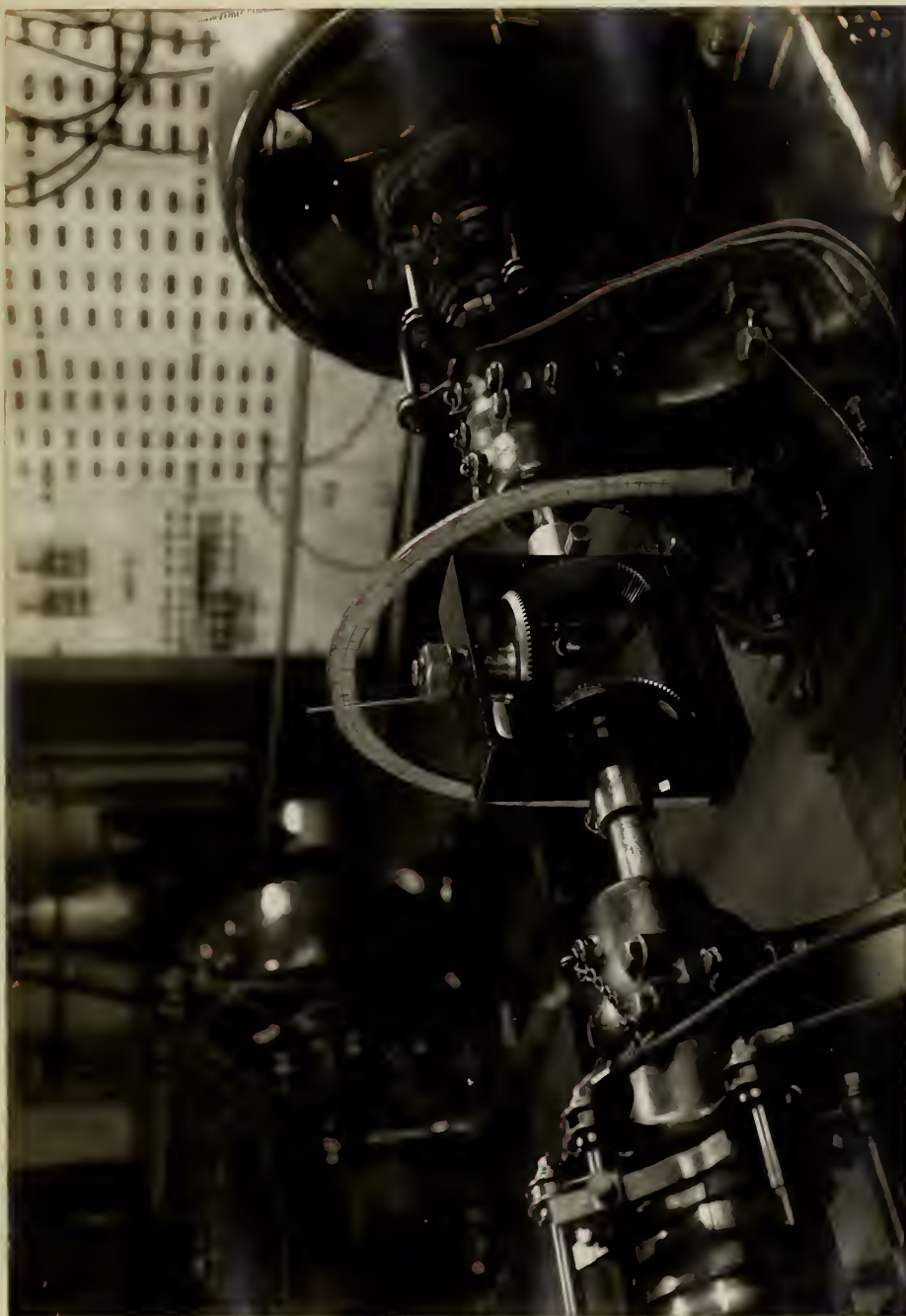


Figure 2. Gear and Scale in Place.

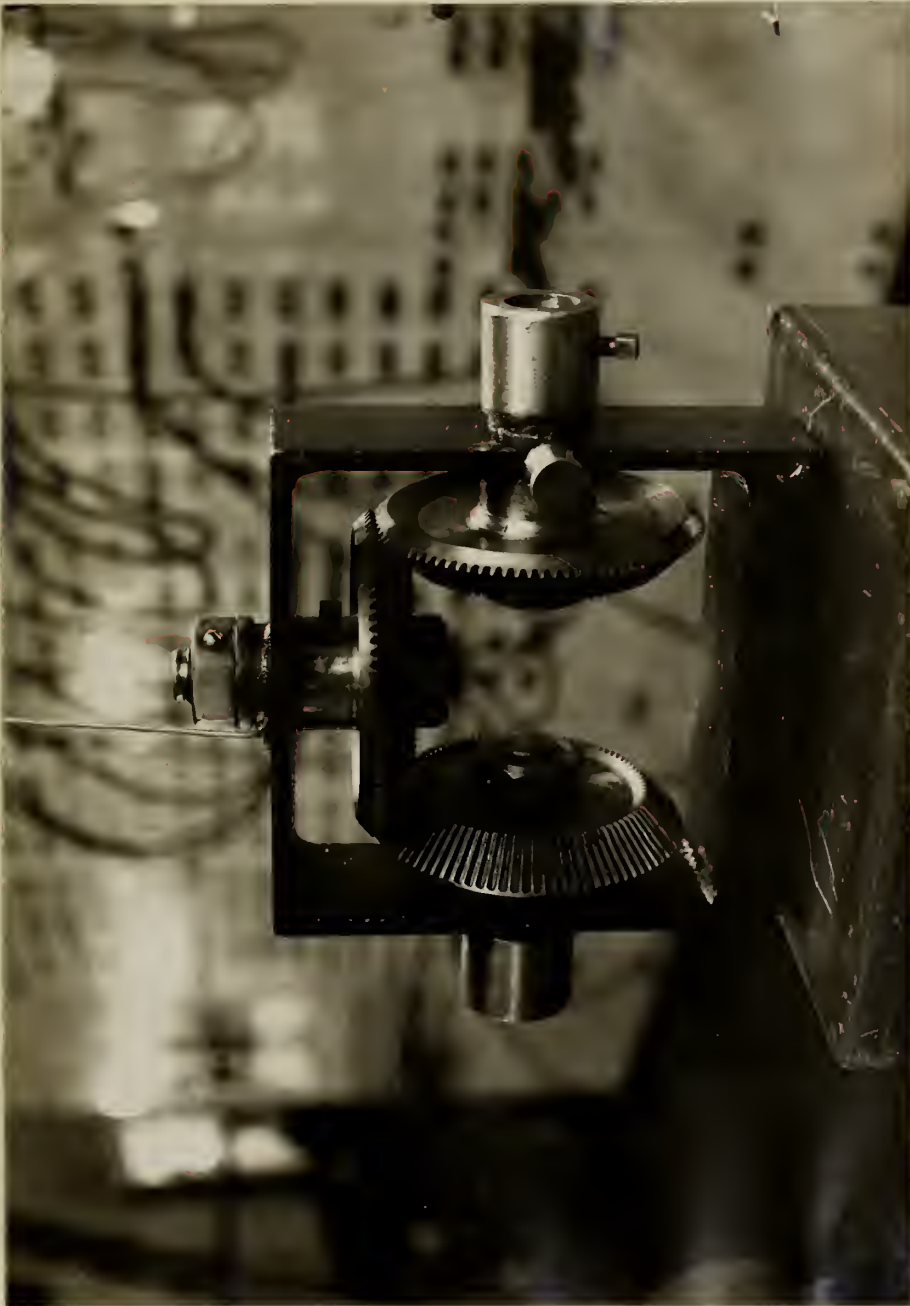


Figure 3, View of Gear.

For the experimental work, two General Electric, 7 1/2 K. W., Double Current Generators were used. These machines were rated by the manufacturer as: 7 1/2 K. W., 110 Volts, 69 Amperes, and 1800 R. P. M. for a frequency of 60 cycles. The armature winding was connected to slip rings, for operation as one, two, or three phase, altho in the experiments the machines were operated single phase only. In order that the action of the two machines could be best observed they were operated in the laboratory side by side, the conditions of a transmission line, being reproduced as nearly as possible by the insertion of resistance and inductance into the circuit between the two machines.

The machines were lined up and a device, consisting of a differential gear and pointer, was used to determine their phase relation during operation. The gearing consisted of a bevel gear attached to the armature shaft of each machine, both gears being in mesh with a pinion having its axis at a right angle to that of the other two. Figures 1, 2, & 3, show the apparatus. Since the two gears were of the same size, and in operation the armature shafts were made to revolve in opposit directions, it is evident that when the two machines were in phase the pointer would remain stationary at some particular point on the scale. The scale being graduated into a system of "electrical" degrees for a four pole machine, any lag between the two machines could be read directly from the scale in "electrical" degrees, after the point of exact synchronous operation as indicated by the pointer, had been determined.

The machines were in all cases driven by means of 220 volt di-

rect current motors, one of the latter being of Western Electric and the other of Sprague manufacture. The size and rating of the motors were essentially the same, and the regulation was for all practical purposes identical.

In order to determine whether or not any differences of machine characteristics existed, the magnetization curves or no-load characteristics and the synchronous impedance curves were determined for normal speed. The curve sheets 1, 2, & 3, show these characteristics to be as nearly alike as it is possible to obtain from ordinary commercial machines.

The machines were first operated in parallel as contiguous machines, (Diagram 1), under various conditions of loading, field excitation, and driving force. The tests, as shown in table 1, were made as follows:

(1) The machine voltages were adjusted and the machines connected in parallel, the "phasing" and synchronizing currents being noted.

(2) The field current of one machine was decreased and that of the other increased, both machine voltages varying by the same amount from normal, and the machines synchronized under no-load conditions. The voltages of the two machines were varied thru as wide a range as possible without producing excessive armature currents.

(3) One machine was operated, under normal conditions as to speed and terminal voltage, under load. The other machine was brought to the same condition of speed and voltage, and connected in parallel with the first one, the armature current and power supplied to the line in each case being noted. The field excitation

of one machine was altered, the effect on current and power supplied to the line being noted.

(4) With the field normally excited, the driving force of one machine was increased, and the effect on the proportion of power furnished by each was determined, as shown in the table.

(5) With the field normally excited, the driving force of one machine was decreased and the effect on distribution of power between the machines observed.

The no load data shows the synchronizing current to be quite small under normal conditions. The synchronizing current cannot be measured with machines under load, which is really the operating condition. The "phasing" current is no indication of the operating characteristics of the machines, since it is merely dependent upon the phase relation and voltage of the machines when the synchronizing switches are closed.

From the data shown above, the following conclusions may be drawn:

(1) Changing the field excitation of either of the two alternators operating in parallel merely changes the voltage and "circulating" current between the two machines, and does not affect the distribution of power.

(2) Changing the driving force of one machine will tend to shift the loads carried by the machines, the machine having it's driving force increased will take a greater portion of the load, or if it's driving force is lessened it will have it's load decreased.

Since synchronous converters are common in alternating current systems of distribution, it was deemed advisable to test the operation of one machine as a motor, the power being supplied by the other one. Data was collected for motor operation under the following conditions, as shown in tables 2 and 3.

(1) The machines were synchronized and the driving force removed from the machine to be operated as a motor. The driving motor was then used as a direct current generator, to apply load to the machine operating as a synchronous motor. Maintaining the motor field and terminal voltage constant, the latter adjusted by means of the alternator field rheostat, observations were taken for various loads on the motor. Readings were taken for constant values of field excitation both above and below normal.

(2) With the impressed voltage kept constant at normal value, and the motor load constant; readings were taken for various values of field current, ranging from considerably below normal to a rather high value. These observations were repeated for various loads on the motor, the angle between the machines, being determined by means of the differential gear.

The tests of the machines as distant alternators were of two classes;

(1) Those at which the load was applied at one end of the line, i. e. adjacent to one machine, as shown in diagram 1, and

(2) Those at which the load was applied at the middle of the transmission line, as shown in diagram 2.

The first set represents such conditions as might be found in the case of a system supplying power to a distant city or manufacturing plant, which also operated a local plant in parallel with the distant one. Such conditions would most likely occur where a water power was utilized, which did not furnish sufficient power to operate the plant, and was supplemented by a local steam plant. From a stand point of regulation, this kind of local distribution offers the greatest difficulties for satisfactory parallel running.

The greater number of tests were made for this kind of distribution for two reasons, viz., Since the severest operating condition is represented in this case, any system giving satisfactory results under these circumstances would without doubt do as well or better under more favorable conditions; and due to the fact that the apparatus at disposal for these experiments rather limited the scope of the tests under the second heading.

The first set of data, table 4, was taken for load distribution at one machine, and for resistance only, in the circuit between the two machines.

The resistance effect was produced by the insertion of two General Electric Company iron grid rheostats, into the circuit as shown in diagram 2. These rheostats were rated as 0-1 ohm, 60-30 amperes, and were each divided into fifty resistance notches. In this particular test rheostat were used in series.

The machines were first synchronized under load with no resistance except that of the leads of the circuit, and the terminal voltage adjusted, after the load had been divided between the two alternators by adjustment of driving forces.

Maintaining the field excitation constant for both machines, resistance was gradually inserted in the circuit between the machines, the effect on voltage, current, power supplied, and phase relation of the two machines being noted. The resistance was increased until the machines fell out of step or hunted excessively. This same operation was repeated for other loads as shown in the table.

It can be seen from the table that the insertion of resistance does not affect the power distribution, but that the phase angle between machines increases with increase of resistance, the exact relation between the values depending upon the load on the machines, i. e., the larger the load the angle with a given value of resistance in the line. Altho the field excitation remains constant in this experiment for each load, the voltage of machine number 1 is seen to increase, while that of number 2 decreases with insertion of resistance. This effect is augmented with increase of load, for any given value of line resistance.

In the case of machine number 2, the current changes very rapidly as resistance is placed in the line, and the actual change for any given resistance seems to be independent of the load. For number 1 the change is very slight compared with that of number 2, and apparently follows no definite law. The phase angle for which satisfactory operation ceases, appears in all cases to be about 50 degrees. Curve 4 shows the relation of the resistance in the line to the angle between the electromotive forces of the two machines.

The next set of data, table 5, was taken with resistance in each of the machine leads. Diagram 3 shows the connections. In this case one of the General Electric Co. rheostats, mentioned

above, was placed in the leads of each machine.

The machines were first synchronized with no resistance in the circuit, the voltage adjusted and the load equally divided between the machines. With constant field current, the resistance in the circuit was changed from time to time, the changes for each rheostat being equal and made at the same time.

The lagging of one machine in this case was inappreciable for any values of resistance that could be used. For the higher values of resistance, the table shows a phase angle of 3 degrees, which however was more of a hunting effect than a constant phase difference between machines. As would be expected the voltage regulation is much better than that shown in table 4, in fact, the voltages bear practically the same relation to each other for all loads. The decrease in current and the increase in electromotive force shown in the table are due to "IR" drop thru the resistance inserted, as no effort was made to adjust load for constant current as the resistance increased.

Table 6 shows the results of operation similar to that of table 4, except that in the first set of data in table 6, the terminal voltage of machine number 1 was kept constant; and in the second set the voltage of number 2 was kept constant. In all cases when the E. M. F. of either machine was raised or lowered in order to bring it to normal value, the adjustment was made by its own field rheostat. This change of course affected the other machine due to the armature reactions in the machines.

In this set of tests the load was changed somewhat from time to time, both by change in bus-bar voltage, and the change in the num-

ber of lamps in the load circuit. The data shows the current to increase rather faster than the load on the machines, as the resistance in the leads is increased. It can be seen that the voltage of one machine cannot be changed without changing that of the other a practically equal amount.

Table 7 shows what is probably the most interesting set of data of the entire set of experiments; at least the behavior of the alternators during the tests was very interesting. The results were obtained with resistance and inductance in the leads of one machine only, the other generator being connected directly to the bus-bars from which the load was taken. The variable resistance consisted of one of the iron-grid rheostats previously mentioned. The inductive effect was obtained by the use of a large reactance coil, or rather two coils in series arranged so that one could move up and down inside the other and connected so that they opposed one another. Thus when one coil was inside the other entirely, the reactance was a minimum, and when entirely removed the reactance was a maximum. The length of each coil was 30 inches; the outer one having a circumference of 30.75 inches, and had 418 turns of number 8 wire; the inner coil was 26.25 inches in circumference, and was composed of 420 turns of number 8 wire. The resistance of the two coils in series was 1.3 ohms, hot. The coil was calibrated for various positions, and the values of reactance from this calibration used in all determinations.

In the first set of observations, the machines were first synchronized under load and the voltage adjusted to as near normal

value as possible, and the load was equally distributed between the machines. For a constant load on the bus-bars, and constant field excitation, readings were taken in the first case, for a constant value of resistance of 1.3 ohms, and a varying inductive reactance in the leads of machine number 1.

The current in machine number 1 is apparently very little affected by the increase of inductance; on the other hand however the current in number 2 is largely increased, without change of power output of either machine. In this set of data the terminal voltages of both machines were decreased, that of number 2 however showed the greatest decrease for a given impedance. The power distribution, as in the previous tests, was unaffected by the increase of reactance until such a point was reached that hunting commenced, when the load was momentarily shifted from one machine to the other to a greater or less extent, depending on the severity of the hunting action. The most noticeable effect of increasing the inductive reactance was on the phase relation of the two alternators as indicated by the differential gear. Until a point was reached where the lag angle of machine number 2 behind number 1, was about 35 degrees, the operation was very satisfactory, the machines being in a very stable state of parallel running. However after this point was passed the machines showed considerable tendency to hunt, and and they would fall out of step with the slightest unfavorable change of conditions in the circuit. The behavior of the machines and instruments, during this process of falling out of step, was very interesting. Machine number 2 would gradually lag farther and farther behind number 1, until there was a phase angle of about

90 degrees between them, when the indicator would suddenly move thru an angle of about 360 degrees, where it would stop for a very short time, held by the rush of current from one machine to the other as indicated by the ammeters. When this rush of current, which was very much smaller than when the machines fell out of step with only resistance between them, had subsided, the indicator moved thru another 360 degrees, and so on, until the load was reduced or some other change was made in conditions of operation so that the machines could be held in step. The rush of current due to falling out of step was too small to do any damage, (due no doubt to the "choking" action of coil used) the only noticeable effect being the flickering of the incandescent lamps, used as load, while the phase relation of the machines changed.

In the second set of observations in table 7, the inductive reactance in the circuit was kept constant at as low a value obtainable with the coil used, and the resistance in the circuit was varied from time to time. The results shown in this test resemble those in table 4 as resistance effects; in that the voltage of machine number 1 increases, while that of number 2 decreases, the field excitation remaining constant; and in the much greater increase of current in the second machine than is shown in the first part of table 7. The machines fell out of step for approximately the same phase difference as above, but for a much less value of total impedance between machines, and there was a greater rush of current when this occurred.

The third set of data was taken for a constant value of inductance, considerably higher than in the second case, and for varying

resistances. The behavior in this case again resembles that of machines in the first test of this set, and falling out of step for about the same lag angle as in both the above cases.

For a value of inductive reactance above 1.85 ohms, and its accompanying resistance, 1.3 ohms, the machines operated in a very unstable state. A comparison of the results of tables (4) and (7) will show that for a given value of total impedance between machines a greater lag angle will exist where this impedance is somewhat inductive, than where the whole effect is due to resistance, and that the falling out of step is not serious where there is considerable inductance between machines. The circulating current is evidently greater in the former case than in the latter, probably due to the choking or restraining action of the inductance coils.

Table number 9 shows the operation of the machines with transformers in the circuit between machine number 1 and the bus-bars from which the power was taken. Two Westinghouse 7 1/2 K. W., 440-110 volt transformers were used in the tests, as step up and step down transformers respectively. The low voltage side of one transformer was connected to machine number 1; the 440 volt coil of transformer number 1 connected to to the 440 volt coil of number 2, and the low tension side of the latter connected to the bus-bars, as shown in diagram 4. The machines were synchronized under no-load conditions. For constant field excitation, various loads were applied to the machines.

The table shows that the voltage of machine number 1 dropped considerably below that of number 2, for full load on machines. This can be explained by the fact that the driving motor of machine

number 2, apparently dropped some of its load as the total load on the machines approached normal full-load value. The next three sets of data, tables 10, 11, & 12, were taken under similar conditions, except that a variable resistance was inserted in the line at different intervals.

The first of these, table 10, shows essentially the same results as does table 4. Table 11 gives the same results except that the voltage of machine number 2 is increased, the variable resistance being, of course, in its leads.

GENERAL CONCLUSIONS.

The greatest difficulty encountered in parallel operation is the matter of engine regulation. While engines are built with devices for regulating the speed to a given number of revolutions per minute, no satisfactory device is known, which will give a perfectly uniform angular velocity during the revolution. Since all governors are primarily dependent upon a change of speed for their operation, it is evident that any shifting of the load on the generator will cause a variation of speed of the prime mover. This trouble is not present to any great extent in a steam turbine plant. The poor regulation of engines affects machines operating in parallel in the same plant as well as distant machines, but in the latter case exceptional poor regulation might cause the machines to fall out of step on account of the impedance of the transmission line restraining the circulating current which normally would flow. One effect of resistance and inductance in transmission is to cut down the circulating current which would otherwise flow for a given phase difference between machines.

When the load is applied to the line in such a manner that there is equal impedance between the load and each machine, the above mentioned is the only effect noticeable, and for good regulation of driving force the stability of the machine is not much affected by ordinary values, or those thru which any amount of power could be satisfactorily transmitted. This statement of course applies in the case of a load uniformly distributed, equally as well.

When however the power is taken from the line adjacent to one of the machines several other effects are observable, besides that mentioned above. When resistance effects alone are present in the line, the voltage of the machine at the distant end of the line will be considerably higher than that of the machines adjacent to the load, even for normal field excitation.

Adjustment of the field rheostat does not better this matter as an increase of voltage of one machine is followed by an approximate equal change in the other one, the only difference being that due to the operation on different parts of the magnetization curve in each case. The load distribution as in the case of contiguous machines is not affected by the variation of field excitation in either machine. The greater the line resistance between the machines the greater the phase angle between them. This effect, up to the limit of satisfactory parallel operation, probably is of no particular interest to the operating engineer, but it is interesting to compare it with that due to inductance. The machines under test with load entirely distributed at one end of the line, showed a lag angle of 50 degrees, before excessive hunting or falling out of step took place. The regulation of the driving motors used in the experiments being much better than could be expected in the case of ordinary reciprocating engines, the hunting was probably much less pronounced than would have been the case if the latter type of prime mover had been used.

The effect of inductance is to increase the angle between the machines for which satisfactory operation ceases, for any given load

on the machines and a given line impedance. Another important consideration is that with high inductance in the line an actually falling out of step is not usually serious. When there is resistance only in the line, a falling out of step is usually always followed by a heavy rush of current, a large variation in the line voltage, and shifting of the load from one generator to another. Where several machines are operating on a long transmission line of large inductance, a single one of them may fall out of step without any noticeable effect except perhaps a slight surge of current.

A very serious trouble in parallel operation where the prime movers are reciprocating engines, is the proper division of load between units of different sizes, since the smaller units tend to run as synchronous motors or are heavily overloaded, with the slightest change in driving conditions.

There are at present very few plants operating in parallel with others at a distance, except for short intervals to shift the load from one station to the other. The main reason for this condition of affairs is that such operation is not satisfactory, except for the most favorable distribution of load.

Summed up briefly, according to the data of this investigation the two most important factors in determining the limits of satisfactory parallel operation of distant machines are; engine regulation and line impedance. The former was of course not investigated experimentally, and due to the limited number and scope of tests made concerning the latter, no attempt was made to give exact relations from the data; the tables showing better than any discussion,

the relations for a given set of conditions. However the data shows that satisfactory parallel operation may continue, even when the voltage drop due to line impedance is as high as 30% to 50% of the normal generated voltage. Since the ordinary practice in electrical distribution limits the line drop to about 10% of the terminal electro motive force, it can be safely concluded that unsatisfactory parallel operation of distant alternators, must be attributed to other causes than transmission line impedance.

TABLE NO. 1.

Alternators operated in parallel as contiguous machines.

E. M. F.	E. M. F.	E. M. F.	Phasing	Syn.
No. 1.	No. 2.	Ter.	Current.	Current.
110	110	110	9	4
115	105	110	26	14
120	100	111	40	26
125	95	112	44	35
128	92	113	44	37

Field excitation of machine number 2 decreased.

E. M. F.	E. M. F.	Current	Current	K. W. Load	K.W.
No. 1.	No. 2.	No. 1.	No. 2.	No. 1.	No. 2.
110	110	24	4	2.70	.26
107	107	28	12	2.70	.10
102	102	33	19	2.70	.05

Driving force on machine number 2 increased.

110	110	24	4	2.70	.26
110	110	12	12	1.50	1.40
110	110	8	16	1.15	1.75

Driving force on machine number 1 decreased.

E. M. F.	E. M. F.	Current	Current	K. W. Load	K. W.
No. 1.	No. 2.	No. 1.	No. 2.	No. 1.	No. 2.
110	110	24	4	2.70	.26
110	110	10	14	1.25	1.50
110	110	5	21	.20	2.30

TABLE NO. 2.

Synchronous Motor Operation.

Generator.				Motor.	
E. M. F.,	K. W.,	I_f ,	Arm. Current,	E. M. F.,	I_f ,
111	1.00	1.65	8	110	1.52
112	1.70	1.77	16	110	1.52
114	2.80	1.90	26	110	1.50
114	3.60	2.00	33	110	1.50
115	4.70	2.15	43	110	1.50
115	5.30	2.30	50	110	1.52
115	6.40	2.45	57	110	1.50
115	7.00	2.45	64	109	1.52

112	1.90	2.15	32	110	1.00
113.5	3.00	2.32	40	110	1.00
114	3.65	2.45	46	110	1.00
116	4.40	2.70	53	110	1.00
116.5	5.30	2.82	58	110	1.00
117	5.80	3.03	64	110	1.00
117.5	6.30	3.12	69	110	1.00
118	6.80	3.30	73	110	1.00

112	2.10	1.10	36	110	2.00
112	3.00	1.20	42	110	2.00
113	3.70	1.40	43	110	2.00
115	5.10	1.57	55	110	2.00
116	6.50	1.80	70	110	2.00

TABLE NO. 3.

Synchronous Motor Operation.

Gen.	Motor	Arm.		Gen.	Motor	Motor	Phase
E. M. F.	E. M. F.	I,	K. W.,	I _f ,	I _f ,	P. F.,	Angle,
110	108.0	33.8	1.95	2.10	.90	.54	6°
110	109.0	19.5	1.80	1.68	1.20	.85	8°
110	108.0	16.5	1.80	1.45	1.40	1.00	10°
110	108.5	18.0	1.90	1.35	1.50	.98	10°
110	108.5	22.5	2.00	1.21	1.60	.82	10°
110	108.8	27.0	2.05	1.10	1.75	.70	12°
110	108.8	40.0	2.25	.90	2.00	.52	16°
110	108.0	55.0	2.60	.75	2.30	.46	20°
110	108.5	58.0	2.50	.75	2.50	.40	24°
110	107.0	37.5	3.20	2.00	.90	.80	8°
110	107.0	29.0	3.15	1.60	1.20	1.00	14°
110	107.5	31.0	3.20	1.34	1.50	.96	18°
110	107.8	44.5	3.42	1.05	1.90	.72	24°
110	108.0	55.5	3.50	.90	2.20	.59	28°
110	107.0	46.5	4.30	2.30	.90	.87	16°
110	106.5	39.0	4.20	1.75	1.20	.99	20°
110	106.0	39.5	4.30	1.50	1.20	1.00	26°
110	106.0	48.0	4.40	1.25	1.90	.87	28°

TABLE NO. 4.

Parallel operation with resistance in the leads of one machine.

E_1 ,	I_1 ,	K.W. $_1$,	E_2 ,	I_2 ,	K.W. $_2$,	I'_f ,	I''_f ,	R,	ϕ
112	37	4.5	110	35	4.2	2.00	1.95	.00	0°
118	39	4.7	108	37	4.2	2.00	1.95	.20	0°
121	39	4.5	104	42	4.5	2.00	1.95	.40	10°
123	39	4.5	100	47	4.5	2.00	1.95	.60	20°
124	40	4.5	96	54	4.1	2.00	1.95	.80	30°
124	41	4.5	93	57	4.5	2.00	1.95	1.00	36°
124	42	4.8	92	62	4.5	2.00	1.95	1.20	44°
124	43	4.9	89	68	4.8	2.00	1.95	1.40	50°
110	47	5.4	107	51	6.1	2.10	2.10	.00	0°
118	46	5.6	103	55	5.9	2.10	2.10	.20	4°
121	48	5.7	100	58	5.7	2.10	2.10	.40	10°
124	51	5.9	95	66	5.5	2.10	2.10	.60	24°
124	52	6.1	87	75	5.4	2.10	2.10	.80	50°
109	62	6.9	105	60	6.4	2.20	2.10	.00	0°
115	58	7.3	102	65	6.4	2.20	2.10	.20	10°
122	60	6.6	95	70	6.0	2.10	2.10	.40	20°
120	56	6.2	87	86	6.0	2.20	2.10	.60	30°
117	57	6.4	80	88	5.8	2.20	2.10	.80	46°

TABLE NO. 5.

Parallel Operation With Resistance in Both Machine Leads.

E_1 ,	I_1 ,	K.W. $_1$,	E_2 ,	I_2 ,	K.W. $_2$,	I_f' ,	I_f'' ,	R_1 ,	R_2 ,	ϕ
111	33.5	4.1	111	34.5	4.1	1.70	1.75	.00	.00	0°
112	32.0	3.8	111	33.0	3.8	1.70	1.70	.10	.10	0°
112	30.0	3.6	111	32.0	3.8	1.70	1.75	.20	.20	0°
112	28.5	3.3	112	31.0	3.7	1.70	1.75	.30	.30	0°
112	27.5	3.2	112	29.0	3.5	1.70	1.75	.40	.40	0°
112	26.0	3.1	112	28.0	3.3	1.70	1.75	.50	.50	0°
113	25.0	3.0	112	27.0	3.2	1.70	1.75	.60	.60	2°
113	25.0	3.0	112	25.0	3.0	1.70	1.75	.70	.70	3°
113	24.0	2.9	112	24.0	2.8	1.70	1.75	.80	.80	3°
113	22.5	2.8	112	22.0	2.8	1.70	1.75	.90	.90	3°
113	22.5	2.6	112	21.0	2.7	1.70	1.75	1.00	1.00	3°

TABLE NO. 6.

Parallel operation with resistance in leads of one machine,
No. 1, only.

E. M. F. of machine No. 1, kept constant.

E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I'_f ,	I''_f ,	Res.
110	0	0	110	0	0	1.45	1.50	0
110	18	1.90	108	11	1.30	1.43	1.50	0
110	21	1.85	104	15	1.20	1.35	1.50	.2
110	23	1.90	101.5	20	1.20	1.30	1.50	.4
110	25.5	2.05	98	24.5	1.30	1.25	1.50	.6
110	26	2.05	96	27	1.40	1.25	1.50	.8
110	38	2.30	94	30	1.50	1.25	1.50	1.0

E. M. F. of machine No. 2, kept constant.

110	0	0	110	0	0	1.45	1.50	0
111.5	18	1.80	110	15	1.60	1.45	1.65	0
115	22	1.85	110	22	1.70	1.45	1.80	.2
117	26	1.95	110	27	1.80	1.45	1.95	.4
120	31	2.40	110	33	2.00	1.45	2.08	.6
121	39	3.00	110	43	2.50	1.45	2.30	.8
121	43	3.50	109	49	3.30	1.45	2.40	1.0

TABLE NO. 7.

Parallel operation with resistance and inductance in the leads of one machine only.

E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I'_f ,	I''_f ,	R,	X,	ϕ ,
112	31	3.60	110	31	3.60	1.65	1.70	0.0	0.0	0°
112	33	3.70	100	43	3.60	1.65	1.70	1.3	1.3	36°
112	33	3.65	100	44	3.65	1.65	1.70	1.3	1.5	40°
110	32	3.60	99	42	3.60	1.65	1.70	1.3	1.8	44°
109	32	3.60	99	43	3.62	1.65	1.70	1.3	2.0	48°
108	32	3.60	99	43	3.65	1.65	1.70	1.3	2.2	52°
107	33	3.70	98	43	3.60	1.65	1.70	1.3	2.4	56°
106	33	3.65	98	44	3.65	1.65	1.70	1.3	2.8	62°
* 104	34	3.60	97	46	3.70	1.65	1.70	1.3	3.1	68°
112	33	3.70	110	31	3.60	1.70	1.70	0.0	0.0	0°
112	33	3.70	100	43	3.60	1.70	1.70	1.4	1.3	36°
115	35	4.00	96	51	4.20	1.70	1.70	1.5	1.3	40°
114	35	4.00	95	53	4.40	1.70	1.70	1.6	1.3	48°
114	35	4.10	94	55	4.40	1.70	1.70	1.7	1.3	54°
113	38	4.20	91	58	4.40	1.70	1.70	1.8	1.3	60°
114	39	4.10	91	58	4.60	1.70	1.70	1.9	1.3	66°
*	Excessive Hunting.					1.70	1.70	2.0	1.3	90°

Note: * Machines fell out of step.

E_1 ,	I_1 ,	K.W. $_1$,	E_2 ,	I_2 ,	K.W. $_2$,	I'_f ,	I''_f ,	R,	X,	ϕ ,
112	31	3.60	110	31	3.60	1.75	1.75	0.0	0.00	0°
110	33	3.90	100	41	3.40	1.75	1.75	1.5	1.85	50°
110	35	4.00	94	45	3.50	1.75	1.75	1.7	1.85	60°
111	37	4.30	90	50	3.50	1.75	1.75	1.9	1.85	72°
*	Excessive Hunting.					1.75	1.75	2.0	1.85	

Note; (*) Machines fell out of step.

TABLE NO. 8.

Data showing the effect of driving force on the regulation of the machines, with resistance in leads of one machine only.

E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I'_f ,	I''_f ,	R,	Mach. No 2 ϕ
110	28	3.50	110	38	4.30	1.75	1.75	0.0	0°
112	28	3.50	108	36	3.90	1.75	1.75	0.1	Lag 1°
115	29	3.50	105	35	3.80	1.75	1.75	0.2	" 3°

Driving force on machine No. 1, decreased.

115	29	3.50	105	35	3.80	1.75	1.75	0.2	Lag 3°
110	10	1.00	110	54	6.30	1.75	1.75	0.2	Lead 5°

Driving force on machine No. 1, increased.

116	30	3.50	108	34	3.60	1.75	1.75	0.2	Lag 3°
120	50	5.80	102	30	1.60	1.75	1.75	0.2	Lag 10°

TABLE NO. 9.

Parallel operation with transformers between machines.

E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I'_f ,	I''_f ,
110	0	0	110	0	0	1.55	1.50
108	10	1.20	110	5	1.00	1.55	1.52
108.5	19	1.90	111	13.5	1.80	1.65	1.52
108.5	29	3.00	111	21	2.50	1.65	1.52
107	33	3.30	110	25	3.00	1.65	1.52
105	40	4.00	109	29	3.40	1.65	1.52
102.5	49	4.75	107	35	4.00	1.65	1.52
100	59	5.60	105	43	4.90	1.65	1.52
98.5	68	6.30	103	48	5.20	1.65	1.52
96	75	6.65	102	50	5.30	1.65	1.52 *
94	83	7.10	100	52	5.50	1.65	1.52

Note; (*) Slight hunting action.

TABLE NO. 10.

Operation with transformers between machines, and variable resistance in leads of machine No. (1).

E_1'	I_1'	K.W. ₁	E_2'	I_2'	K.W. ₂	I_f'	I_f''	R_1'
109	44	4.45	111	46	4.10	1.60	1.72	0
112	41	4.25	110	35	4.0	1.60	1.72	.1
114	39.5	4.30	107	36	3.9	1.60	1.72	.2
116	39	4.20	105	37	3.9	1.60	1.72	.3
117	38	4.25	103	39	3.7	1.60	1.72	.4
118	39	4.15	101	40	3.7	1.60	1.72	.5
118.5	40	4.00	100	42	3.65	1.60	1.72	.6
119	38.5	4.00	98	45	3.70	1.60	1.72	.7
120	39.5	4.10	95	47	3.80	1.60	1.72	.8
119.5	39.5	4.10	94	49	3.80	1.60	1.72	.9
119.5	40	4.20	93	50	3.80	1.60	1.72	1.0

TABLE NO. 11.

Operation with transformers between machines, and variable resistance in leads of machine No. (2).

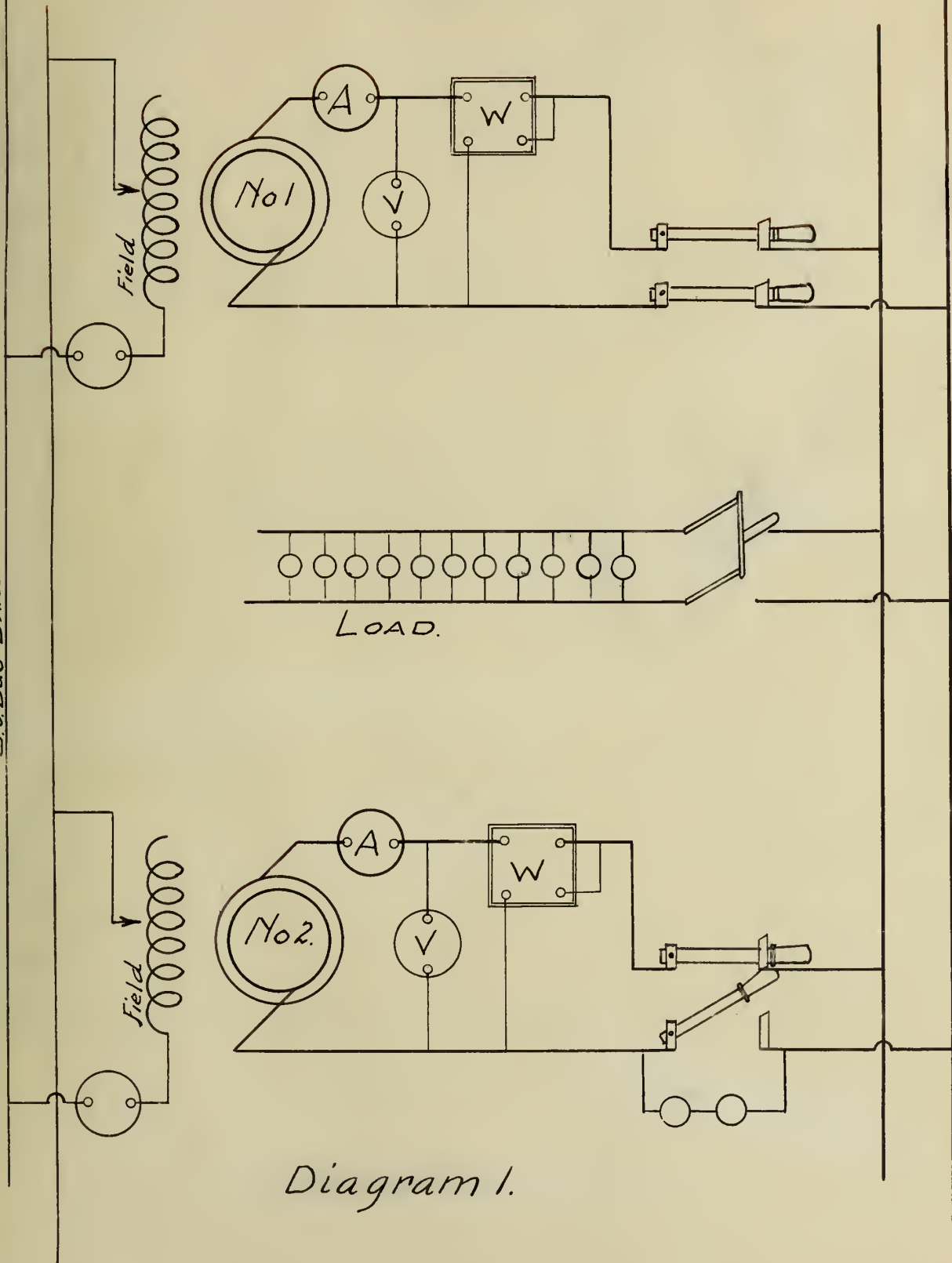
E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I_f ,	I_f'' ,	R_2 ,
107.5	40.5	4.10	110	45	4.2	1.56	1.67	0
105	41	3.95	112	45	4.1	1.56	1.67	.1
102	41.5	3.85	113	44	4.05	1.56	1.67	.2
100	42.5	3.80	114.5	43.5	4.00	1.56	1.67	.3
98	44	3.70	115	43	4.00	1.56	1.67	.4
98	46	3.9	116	42.5	3.85	1.56	1.67	.5
96	47.5	3.85	117	43	3.90	1.56	1.67	.6
95	49.5	3.75	118	43.5	3.90	1.56	1.67	.7
93	51	3.75	118	44	4.00	1.56	1.67	.8
91.5	53.5	3.75	118	44	3.90	1.56	1.67	.9
89	56	3.75	118	45.5	4.1	1.56	1.67	1.0

TABLE NO. 12.

Operation with transformers between machines, and variable resistance in leads of both machines.

E_1 ,	I_1 ,	K.W. ₁ ,	E_2 ,	I_2 ,	K.W. ₂ ,	I_f' ,	I_f'' ,	R_2 ,	R_1 ,
108.5	41.5	4.20	111	37	4.4	1.74	1.57	0	0
111	38.0	3.85	112	33	3.9	1.74	1.57	.2	.2
113	35.0	3.65	111	30	3.5	1.74	1.57	.4	.4
115	31.5	3.40	110	27	3.2	1.74	1.57	.6	.6
116	28.0	3.20	111	24	3.0	1.74	1.57	.8	.8
117	26.5	2.95	112	21	2.7	1.74	1.57	1.0	1.0

D.C. BUS BARS



A.C. BUS BARS.

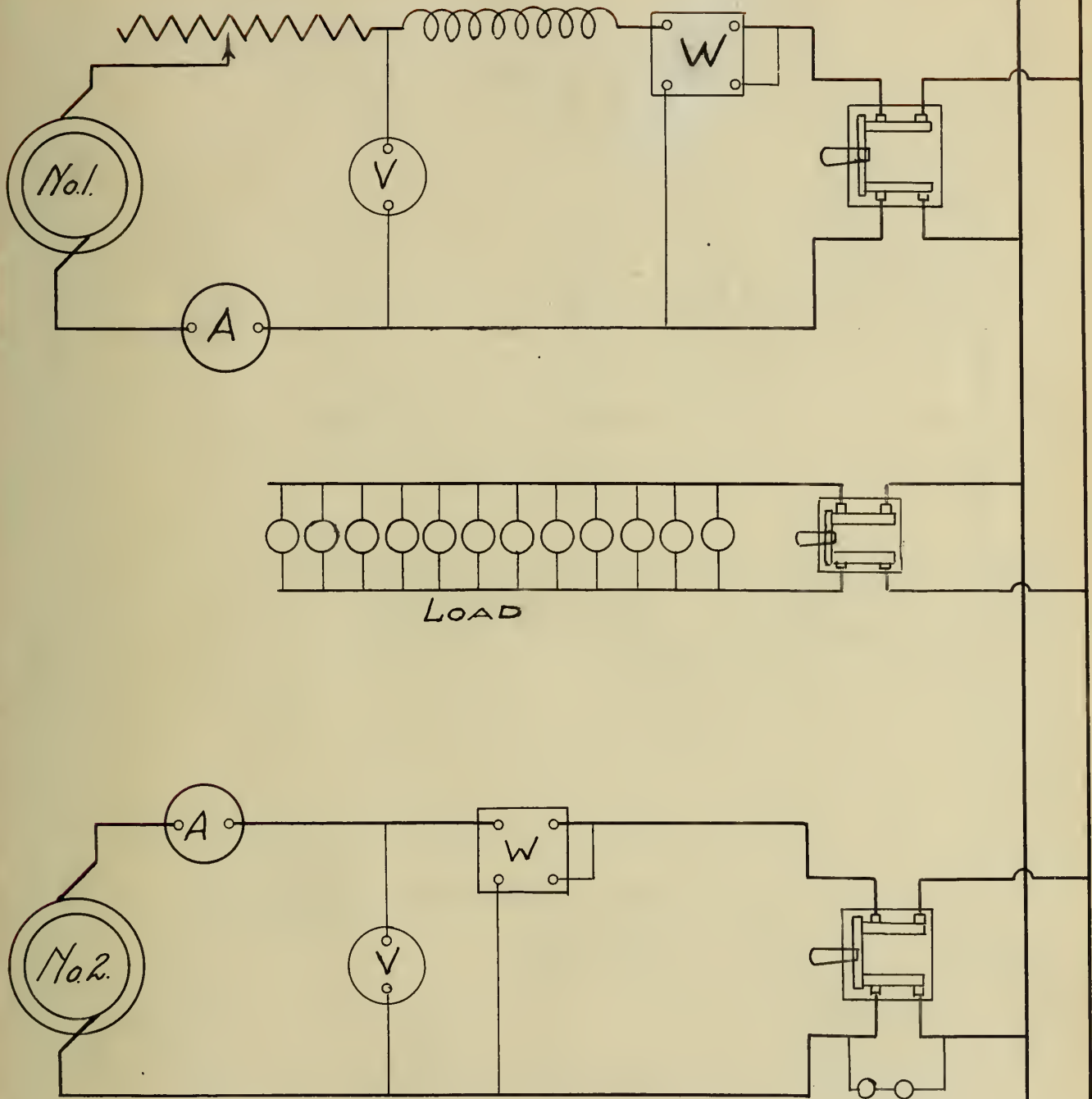
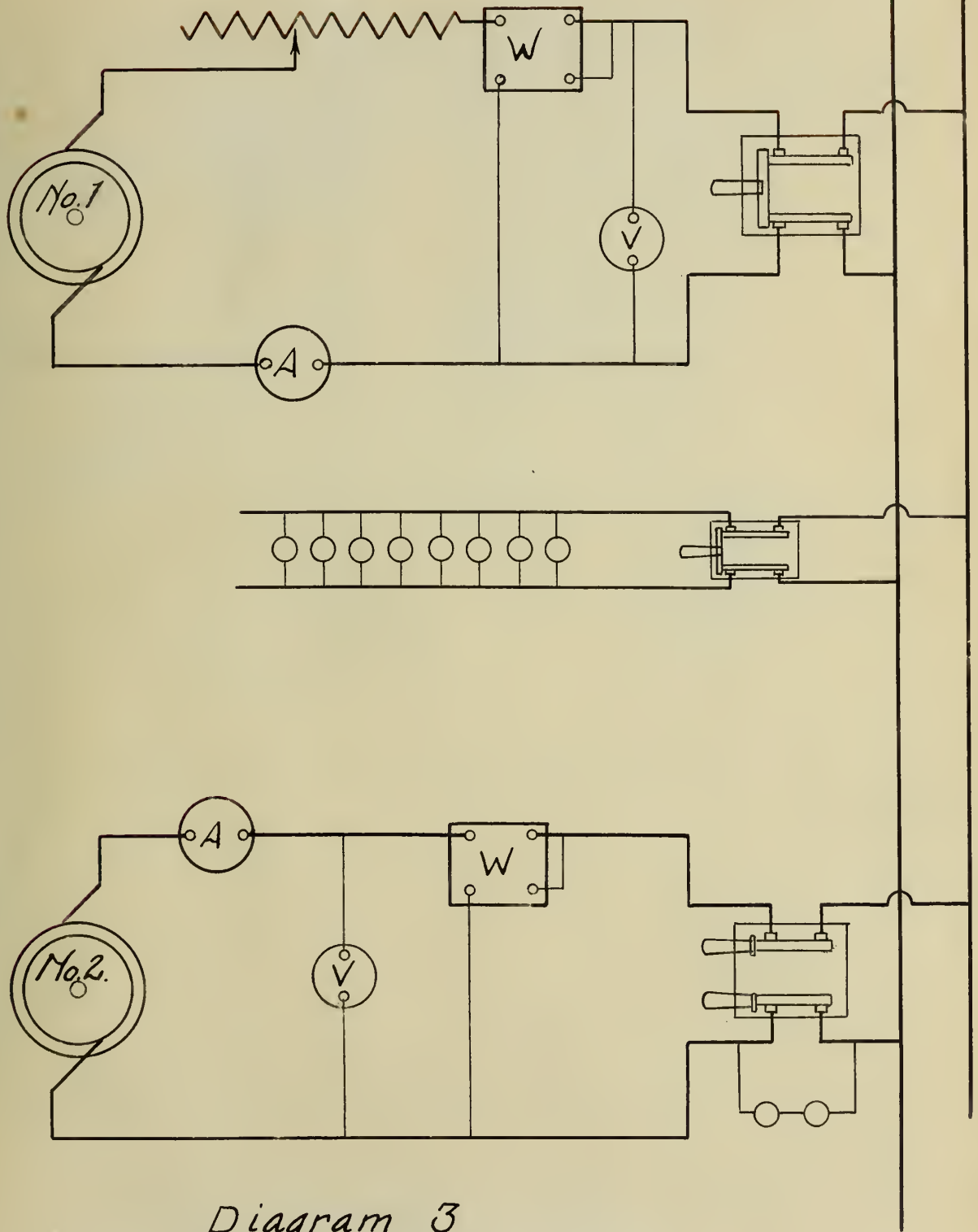


Diagram 2

*Diagram 3*

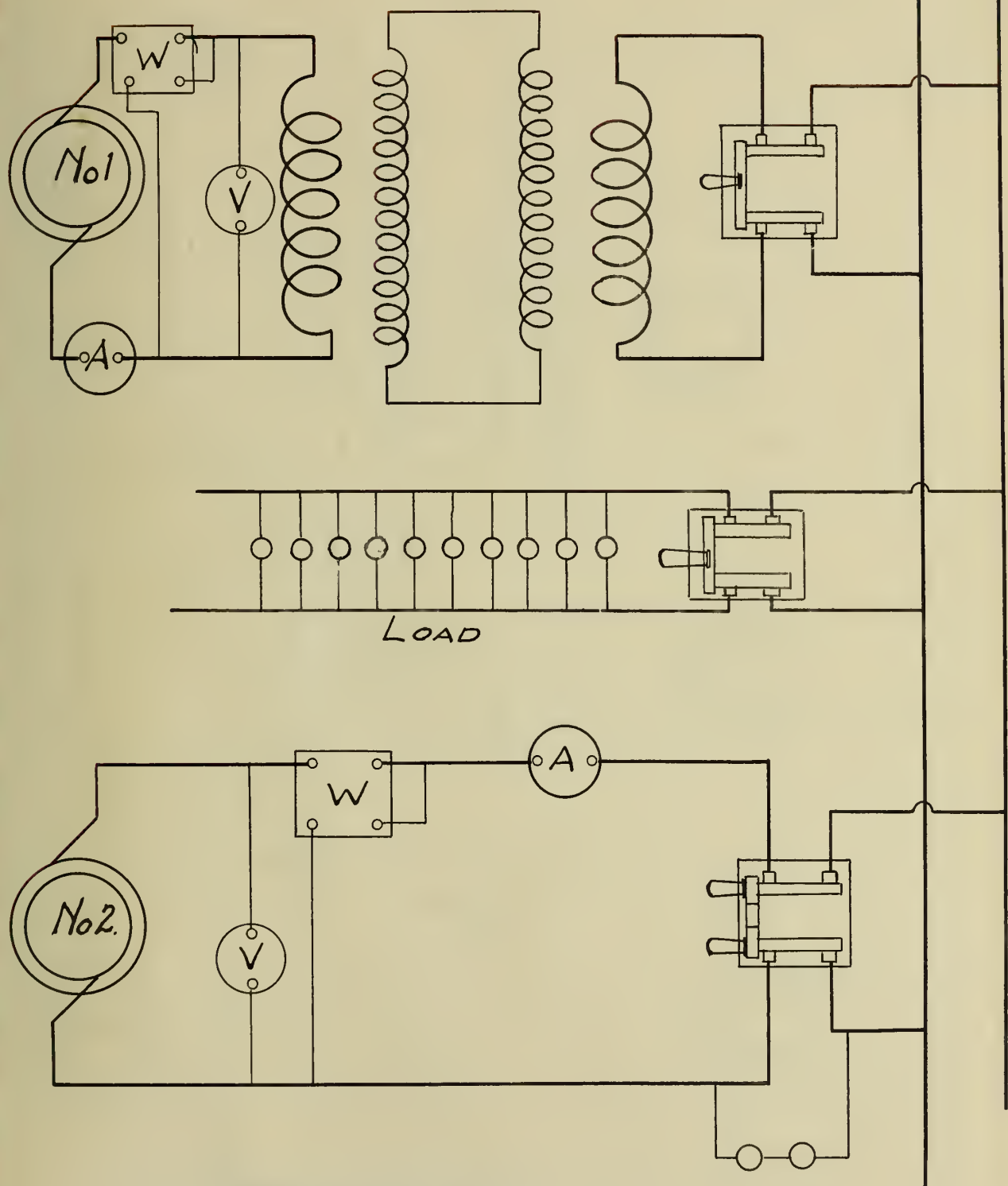
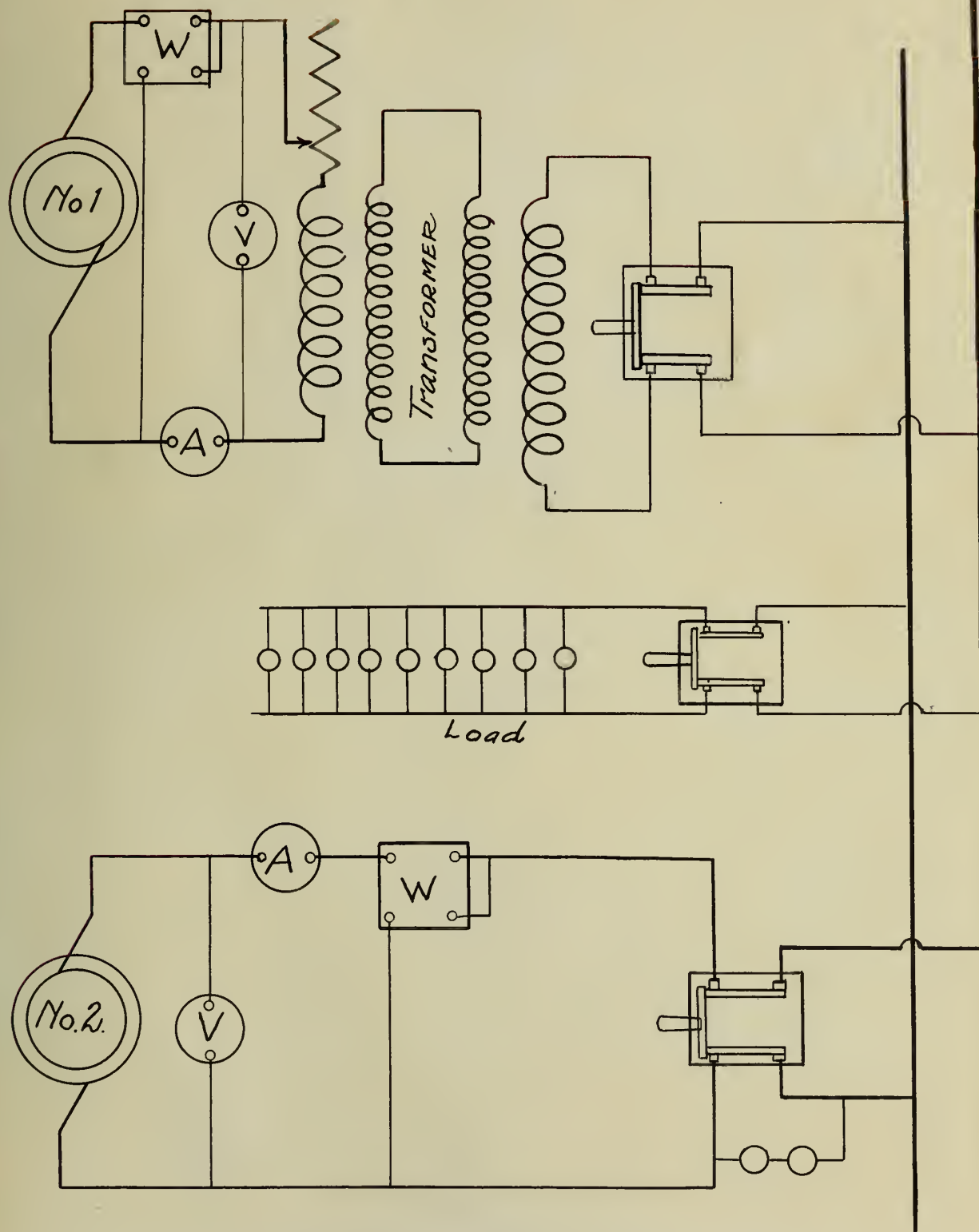
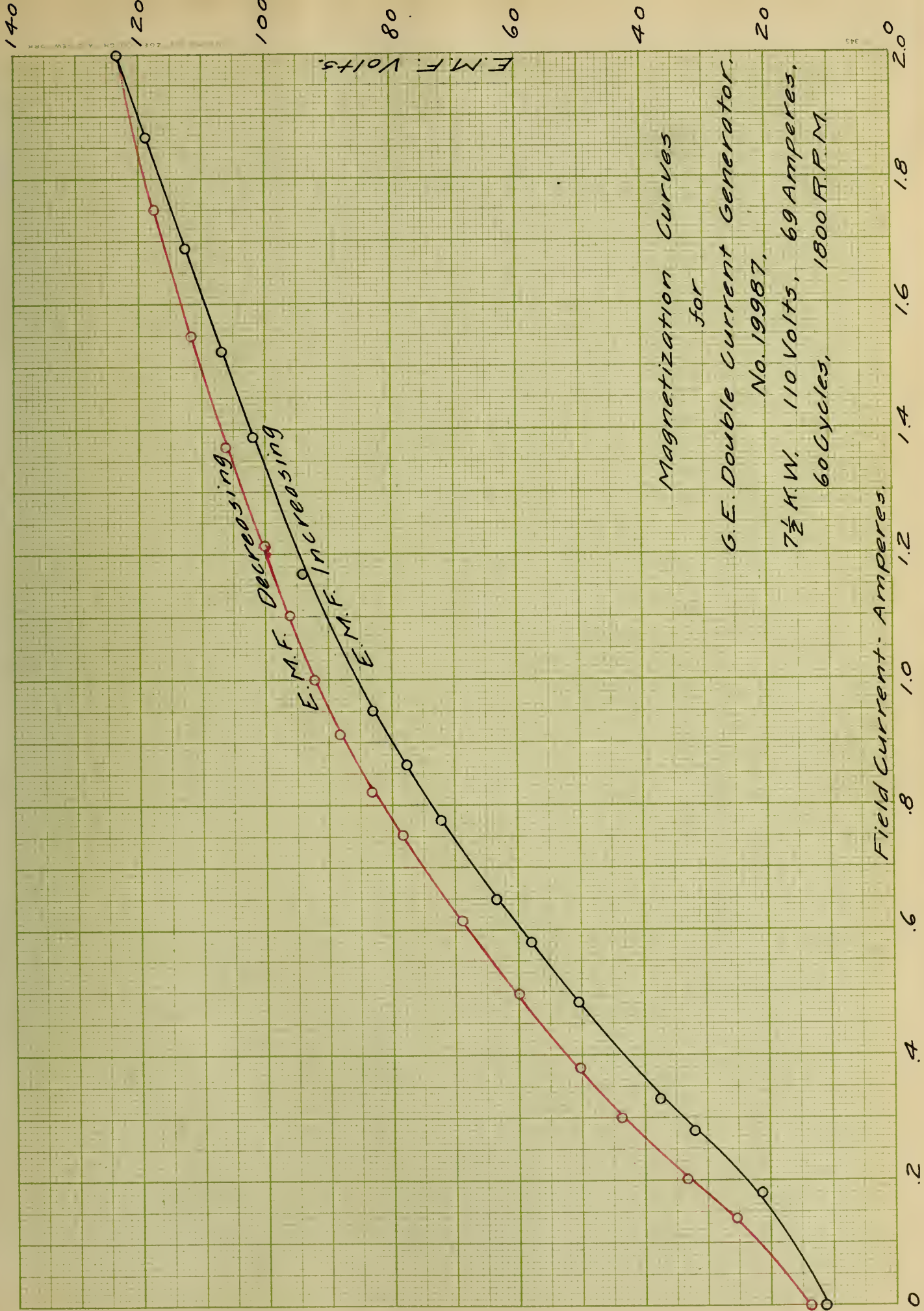
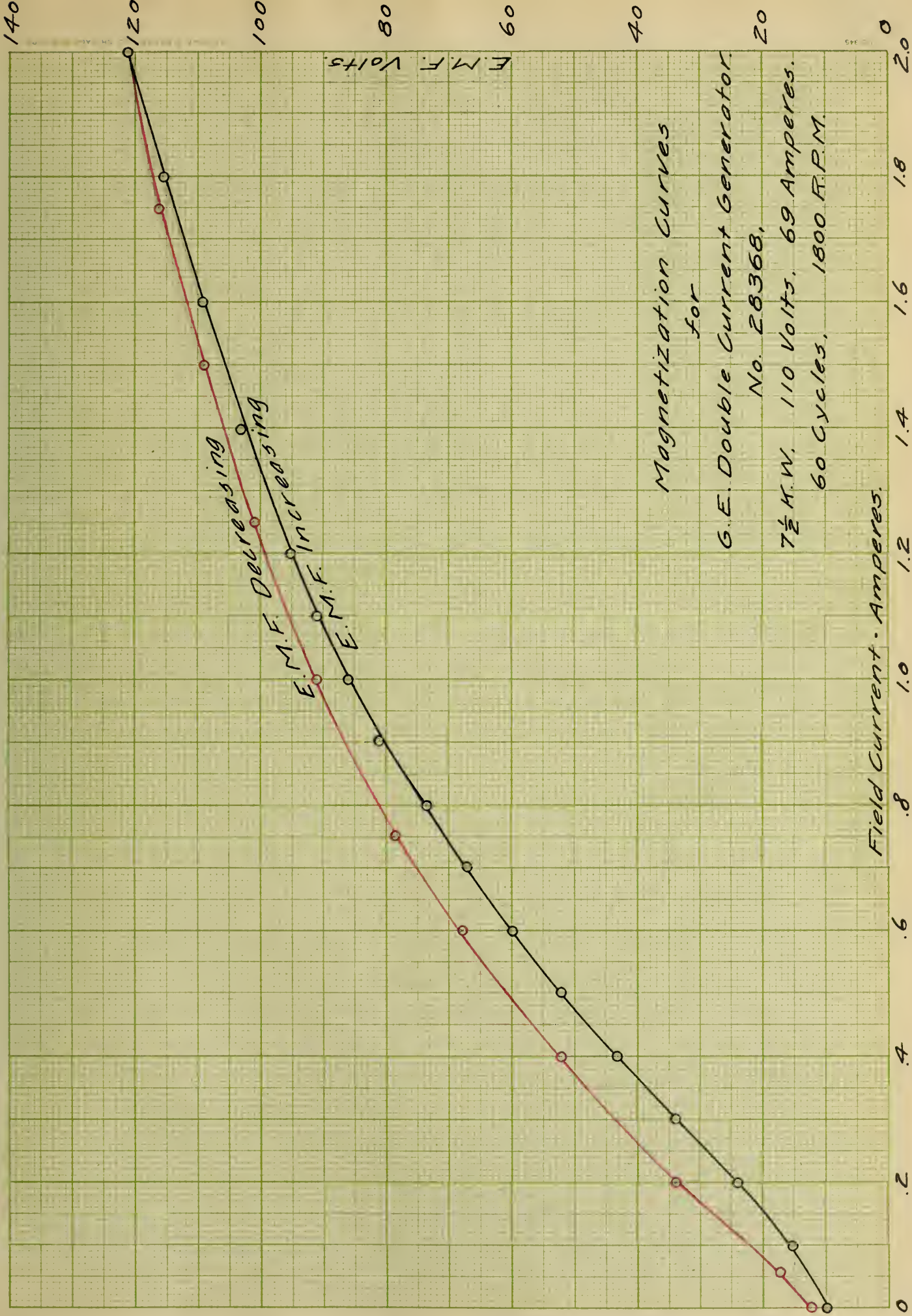
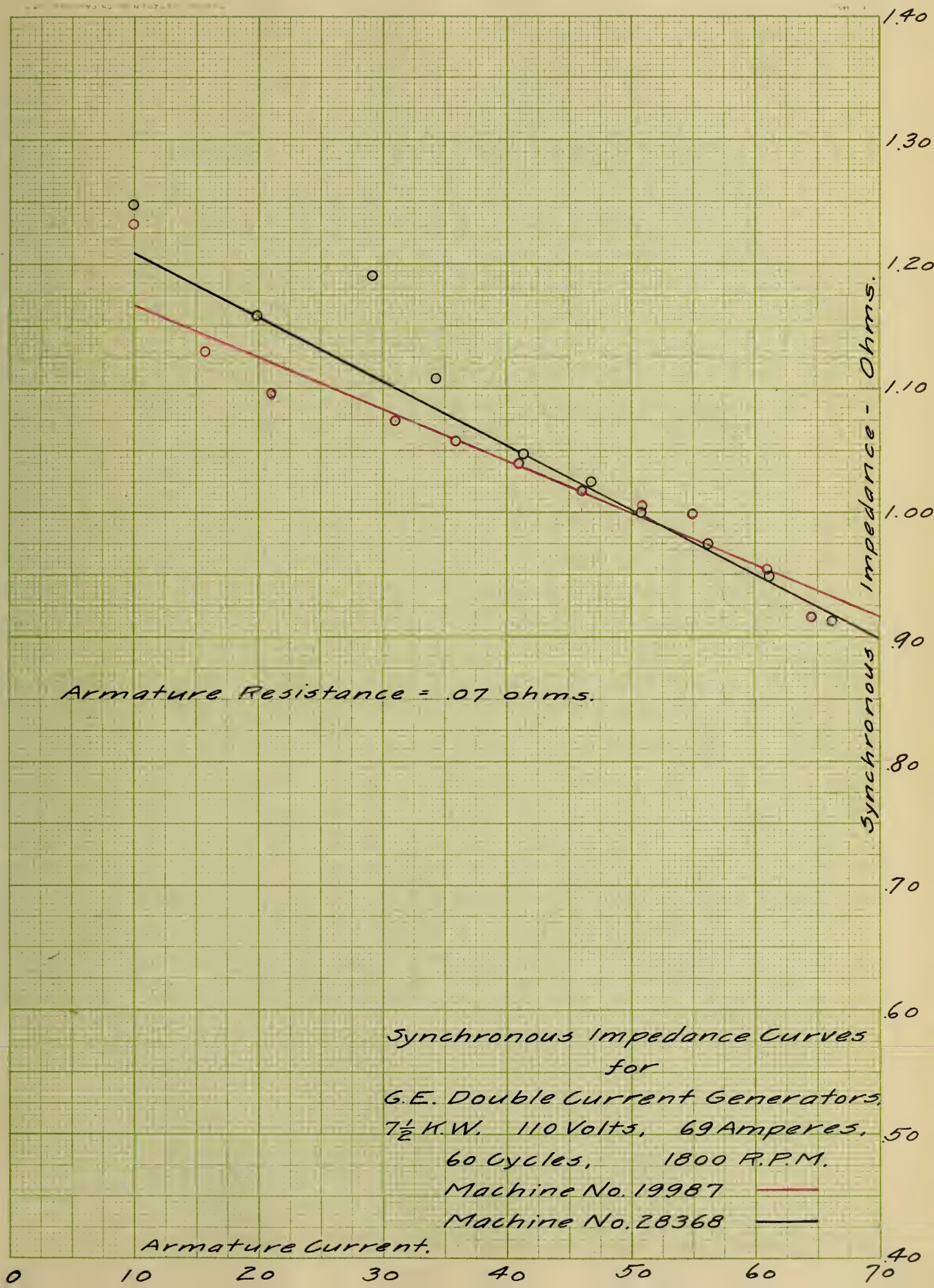


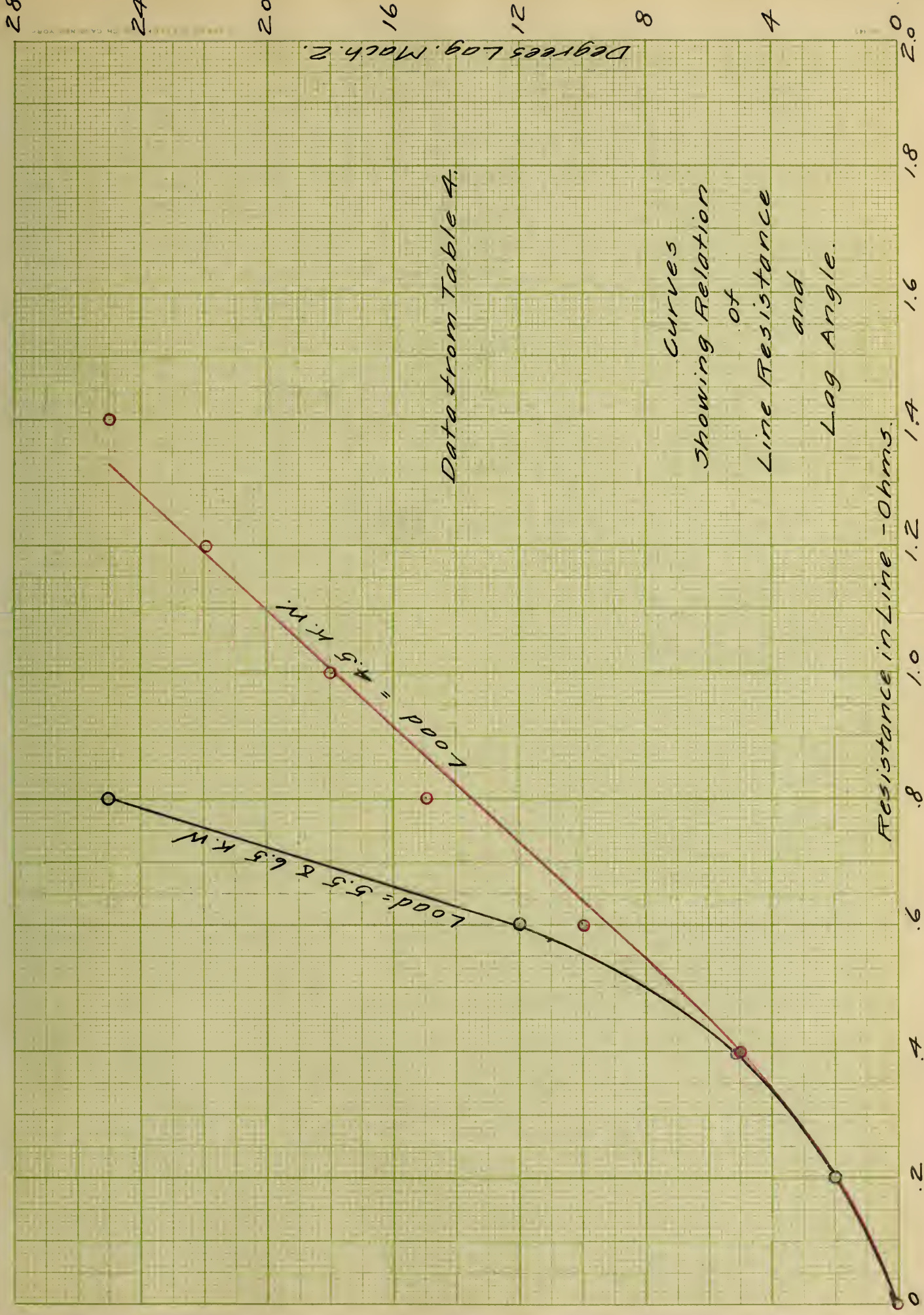
Diagram 4.

*Diagram 5.*









Data from Table 4:

Curves
Showing Relation
of
Line Resistance
and
Lag Angle.





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